

PATENT  
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APPLICATION FOR UNITED STATES LETTERS PATENT

for

APPARATUS AND METHOD FOR RAPID FAULT DETECTION AND  
TRANSFER IN A UTILITY-INTERACTIVE UNINTERRUPTIBLE POWER SUPPLY

By

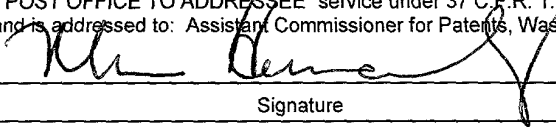
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1       **CROSS REFERENCE TO RELATED APPLICATION AND PRIORITY CLAIM**

2           This application claims the benefit of Provisional U.S. Patent Application Serial  
3       No. 60/208,617, entitled "Apparatus And Method For Rapid Fault Detection And  
4       Transfer In A Utility-Interactive Uninterruptible Power Supply", naming the same  
5       inventors as identified herein and filed June 1, 2000.

6                       **BACKGROUND OF THE INVENTION**

7           The double conversion topology has been the uninterruptible power supply (UPS)  
8       standard for high performance topologies for the last 30 years. Double conversion  
9       provides the ultimate isolation of the critical load from the anomalies present on the  
10      utility electric lines. Some drawbacks of the double conversion topology are that the input  
11      rectifiers tend to draw currents at poor power factors and also tend to introduce  
12      harmonics, and performance is inconsistent throughout the load range. Filters improve  
13      the performance of double conversation systems but do not remedy it.

14          Recently, another topology has been presented for use as a high performance  
15      topology suitable for critical loads. The utility interactive topology does indeed have  
16      appeal as it provides the ideal load to the utility, drawing power at near unity power  
17      factor and at low harmonic distortion throughout its load range. Additionally, utility  
18      interactive topologies exhibit greater efficiencies than the classic double conversion  
19      topologies for certain load types. On the downside, utility interactive topologies do not  
20      protect the critical load as well from utility line anomalies. Among other shortcomings,  
21      certain types of utility faults will pass through the utility interactive system and disturb  
22      the critical load. The occasional passing through of utility line faults with this topology is  
23      due to the inability of the input coupling switch to disconnect in a quick enough fashion.  
24      Ordinary inverse-parallel connected thyristors are often used for this purpose due to their  
25      characteristics that make them very well suited for this application. Unfortunately, one

drawback of thyristors is that they cannot achieve the off or blocking state without having the applied current achieve a zero value.

### SUMMARY OF THE INVENTION

An object of the present invention is to ameliorate the system output waveform disruptions that occur due to input utility line disturbances. The pass through of disturbances that can not be sufficiently attenuated by the normal operation of the utility interactive power converter can only be stopped by rapid disconnection of the input coupling switch means. Two techniques are disclosed that accomplish this. The first technique is suitable for use with switches that require the current to achieve zero for commutation, such as thyristors—Silicon Controlled Rectifiers (SCRs), for example. This technique operates one or both of the inverters in such a manner to cause the line current to achieve zero value in a time period during which the net output disturbance is of little concern. The second technique uses a switch that can be self commutated or uses a non self-commutating switch with auxiliary commutation circuit elements. Also disclosed are several variations of a voltage clamping scheme that is required to deal with the energy released by the line circuit inductances during commutation.

### BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a high level block diagram of a typical offline UPS.

Fig. 2 is a high level block diagram of a typical line interactive UPS.

Fig. 3 is a high level block diagram of a typical online, double conversion UPS.

Fig. 4 is a high level block diagram of a delta conversion UPS.

Fig. 5 is a one-line diagram of a line interactive, delta conversion UPS employing a naturally commutated fast utility disconnect switch in accordance with the present invention.

Fig. 6 is a one-line diagram of a line interactive, delta conversion UPS employing a self commutated fast utility disconnect switch and one alternative snubber circuit in accordance with the present invention.

Figure 7 is a one-line diagram of a line interactive, delta conversion UPS employing a self commutated fast utility disconnect switch and another alternative snubber circuit in accordance with the present invention.

Figure 8 is a one-line diagram of a line interactive, delta conversion UPS illustrating connection of a current or voltage sensor used in control of the fast utility disconnect.

Figure 9 is a one-line diagram of a line interactive, delta conversion UPS employing a self commutated fast utility disconnect switch and another alternative snubber circuit in accordance with the present invention.

Figure 10 is a one-line diagram of a line interactive, delta conversion UPS employing a self commutated fast utility disconnect switch and another alternative snubber circuit in accordance with the present invention.

Figure 11 is a one-line diagram of a line interactive, delta conversion UPS employing a self commutated fast utility disconnect switch and another alternative snubber circuit in accordance with the present invention.

## DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

The mission of an uninterruptible power supply (UPS) is to protect a critical load from all power disturbances present on the utility power grid. The UPS accomplishes this result by providing a steady, continuous power supply. Several types of utility

1 disturbances are commonly found, including transients, sags, surges, brownouts,  
2 blackouts and faults.

3 Utility faults are short circuits that occur when a phase line is inadvertently  
4 connected to a neutral (or ground) or to different phase line. Fault conditions can occur  
5 anywhere in a power grid, and may be caused by auto accidents, lightning, activities in-  
6 plant or within neighboring or remote plants.

7 In the case of phase-to-neutral faults, the phase and neutral voltages will move  
8 close together. This will last for a limited period of time and then be terminated by an  
9 upstream overcurrent protective device opening at least the faulted phase. Because of the  
10 massive energy concentration at the fault, the fault may disconnect itself before any  
11 protective action. It should be noted that no matter what happens, all the downstream  
12 loads remain connected. Consequently, during the fault the UPS feeder remains in a low  
13 impedance state and appears as a short circuit. Open circuit, high impedance utility  
14 failures are unusual.

15 In the case of phase-to-phase faults, a shorted condition causes both phase  
16 voltages to move together and behave as one. This presents an apparent phase shift and  
17 an averaging of the voltages. As before, the fault may clear itself. If a circuit breaker is  
18 upstream of the fault then all three phases could open, likely in an erratic fashion because  
19 of arcing in the breaker. If fuses are upstream of the fault then other possibilities exist.  
20 The shorted phases may both open or one of the two phases may open.

21 The simplest type of UPS is the off-line topology, shown in Figure 1. Under  
22 normal operating conditions, AC power from the utility passes from the input 101 straight  
23 through the UPS to the critical load connected to output 107. A charger 102 or “4-

1 quadrant converter” converts AC power from input 101 to DC power to charge battery  
 2 103. Inverter 104 converts DC power from the battery to AC power that supports the  
 3 critical load when the utility fails. Normally inverter 104 is operating in the stand by  
 4 mode, keeping the battery 103 charged. If the utility power goes out of tolerance,  
 5 inverter 104 powers the load, drawing energy from the battery 103.

6 The off-line topology is labelled “single-conversion” because power is converted  
 7 only one time. When the normal power source is available, a small amount of power is  
 8 converted from AC to DC to maintain battery charge. When input AC power goes out of  
 9 tolerance, the UPS converts DC battery power to AC to support the load. During the  
 10 transition from normal power to battery power, there is an output voltage disturbance as  
 11 the output inverter changes from idling to carrying 100% of the connected load.

12 A single conversion UPS is inexpensive and efficient in normal operation. It is  
 13 ideal for home use or for powering individual computer workstations running non-critical  
 14 applications that only require outage protection. Single conversion UPS products  
 15 sometimes have surge suppression and/or “buck and boost” circuits to compensate for  
 16 high or low input voltage, but otherwise do not provide significant input power  
 17 conditioning.

18 The next step upward is the line interactive topology, shown in Figure 2. The line  
 19 interactive topology resembles the offline topology, but includes a transformer or  
 20 inductor 202 in series between the utility power source and the load. This inductor  
 21 enables the UPS inverter 203 to “interact” with incoming power and provide power  
 22 conditioning to the critical load. Typically the 4-quadrant inverters used in line  
 23 interactive UPS are constant voltage devices. They adjust to shifting loads by changing

1 their output phase angle. Because the phase angle cannot be shifted quickly without  
2 potential disruption of the critical load the difference in power required to compensate for  
3 the disturbance is extracted from the battery 204. The resulting frequent hits on the  
4 battery shorten battery life. Another limitation of line interactive products is that they  
5 cannot completely isolate the critical load from the input line without operating on  
6 battery power. Small frequency perturbations and power quality disturbances get passed  
7 directly to the critical load. Without electrical isolation, common-mode noise also passes  
8 right through the UPS to the critical load.

9 The premium UPS topology is the true on-line or double conversion UPS  
10 illustrated in Figure 3. Input 301 is connected to rectifier 301, which rectifies incoming  
11 AC power to DC power to supply the internal DC bus 308 of the UPS. Output inverter  
12 304 takes the DC power from DC bus 308 and produces AC power to support the critical  
13 load connected at output 307. Battery 303 is attached to DC bus 308 and is float charged  
14 during normal operation. When the input power is out of the tolerance limits, battery 303  
15 provides power to support inverter 304 and the critical load. Some advantages of this  
16 configuration include: load isolation, output voltage stability, output voltage and  
17 frequency independence, capability for separate inputs for the normal and bypass source,  
18 backfeed prevention, and mature and well-understood technology.

19 The traditional double conversion online UPS is designed to operate despite any  
20 type of utility line fault or other utility line disturbance. This operation results because  
21 the input rectifier 302 chops up the incoming utility voltage and turns it into direct  
22 current (DC) voltage for the battery 303. Within reason, battery 303 can tolerate minor  
23 disruptions on the energy supply.





1 In the normal mode (which means a nominal input waveform and a linear load on  
2 UPS), the utility disconnect static switch 402 is closed. Utility power is therefore  
3 supplied directly to the output 408.

4 When the input voltage is present but not at its nominal value, series inverter 404  
5 injects a voltage into buck/boost transformer 403 to add or subtract from the input  
6 voltage. This creates a regulated output voltage, similar to some electronic voltage  
7 regulators.

8 When the input power goes out of tolerance limits, main inverter 406 will supply  
9 full output power. The utility disconnect static switch 402 is turned off to prevent  
10 backfeeding. Power failures that will activate main inverter 406 include the input voltage  
11 going outside the regulation range of series inverter 404 and deviations of the input  
12 power source frequency or phase angle.

13 Providing load harmonic current and power factor correction requires that main  
14 inverter 406 operate to inject the required compensation currents, either harmonic  
15 currents and fundamental frequency reactive currents. Series inverter 404 operates to  
16 correct the voltage. The function of the inverter in normal operation is to stabilize the  
17 output voltage and to supply reactive or harmonic power if so required by the load. The  
18 amplitude and phase of the main inverter 406 can be controlled as to maintain the desired  
19 state of charge on the battery and thereby compensate for the power flow to or from the  
20 series inverter.

21 Like the offline UPS, the line interactive UPS can be efficient because it supports  
22 the entire critical load only during power disturbances. Compared to the offline UPS, the

line interactive UPS pays a small efficiency penalty for the series inductor (or transformer) 403 and for losses associated with their power conditioning functions.

Line-interactive and offline UPS products are notoriously susceptible to input faults, which is why they typically have a utility disconnect static switch and fast blowing fuses on the input, attempting to prevent feeding power from the DC bus back to the utility. In a utility interactive UPS the utility waveform is used as the foundation to construct the output waveform. The utility interactive UPS makes modifications to the raw utility waveform to make that utility waveform more suitable as an output waveform for the critical load. For instance, if the incoming voltage is too low, voltage is added to raise the output voltage to the proper level. Similarly, incoming voltage that is too high is reduced. Harmonics are subtracted from the input to present a cleaner sine wave at the output.

At first appearance this method seems to provide a high-efficiency, utility-friendly means to present a quality waveform to a critical load. It is very important, however, to recognize the limitations of this system. Because the output critical bus waveform is constructed from the utility sinewave, frequency independence is impossible without battery operation.

An analysis of a typical utility interactive UPS design illustrates that utility waveform corrections up to 20% of the input voltage can be made. The limit employed in such a system is arbitrary, and is typically chosen with cost in mind. For disturbances beyond the 20% limit, the UPS must disconnect the utility input and run on battery power. Under certain utility conditions, this results in repeated battery hits that shorten battery life. To compound the problem, under some utility conditions the UPS cannot





1 phase circuit. Alternating current ("AC") power is received at input 501. The critical  
2 load to be powered is connected to the UPS at output 515.

3 During normal operation, AC power passes through a naturally commutated fast  
4 utility disconnect 502. The fast utility disconnect is comprised of two silicon controlled  
5 rectifiers ("SCRs") 502a and 502b connected in anti-parallel. In a three phase system,  
6 each phase of the fast utility disconnect would comprise a pair of anti-parallel-connected  
7 SCRs. The SCRs are gated to allow power to pass from input 501 to low-pass filter 503,  
8 which serves to provide some conditioning of the incoming voltage. Low-pass filter 503  
9 is a second order filter comprised of inductor 504 and capacitor 505. Other filter designs  
10 which are well known to those of ordinary skill in the art may also be used.

11 AC power to be delivered to the critical load then passes through one winding of  
12 transformer 506, which is connected in series with the UPS bus 56. The purpose of  
13 transformer 506 will be discussed in more detail below. The power for the critical load  
14 then passes to the critical load by way of capacitor 514, which serves as a filter capacitor  
15 to reduce small high frequency components on the output waveform and also serves to  
16 minimize the effects of load transients on the output voltage.

17 The second winding of transformer 506 is connected to inverter 507, which is  
18 called a "series inverter" Series inverter 507 is comprised of switching devices 507a and  
19 507b, which are typically power transistors. In a three-phase system, six switching  
20 devices would be used, two per phase. One purpose of series inverter 507 is to make up  
21 any difference between the desired voltage at UPS output 515 and the voltage supplied at  
22 input 501. Inverter 507 also controls the input power factor of the UPS by drawing  
23 current from input 501 that is sinusoidal and in phase with the input voltage. Inverter

1 507, in conjunction with inverter 511, is also used to maintain the charge on battery 508.  
2 General principles related to design of such inverters and their controllers are well known  
3 to those of ordinary skill in the art.

4 The voltage generated by series inverter 507 is impressed between positive DC  
5 voltage rail 509a and negative DC voltage rail 509b, which serve as the DC bus for the  
6 UPS system. Battery string 508 comprising batteries 508a and 508b, is connected  
7 between these DC voltage rails, as are capacitors 510a and 510b, which serve to  
8 minimize voltage transients on the DC bus. Output inverter 511 also draws power from  
9 or supplies power to the DC bus depending on the mode of operation.

10 Inverter 511 is the main output inverter and is designed to provide full output  
11 power to the critical load connected at output 515. Output inverter 511 comprises two  
12 switching devices, illustrated as power transistors 511a and 511b. In a three phase  
13 system, a total of six power switching devices would be used, two for each phase.  
14 Inverter 511 keeps the output voltage stable and regulated, whether the system is running  
15 on AC power from input 501 or DC power from battery 508. If the AC power supplied at  
16 input 501 is within the appropriate tolerances for the critical load, then inverter 511 is  
17 unloaded. Inverter 511 is operated to produce an acceptable voltage, and injects power  
18 and/or correction current to the UPS system bus through inductor 512, which serve to  
19 smooth the current supplied to the output. Design of such inverters and their controllers  
20 is well known to those of skill in the art.

21 When the input lines fail, it becomes necessary to disconnect the UPS from the  
22 input lines to prevent power generated by inverter 511 from backfeeding the faulted  
23 utility through UPS input 501. This is necessary to prevent: (1) the safety hazard that

1 would be presented by energizing the faulted input lines, (2) the disruption to the critical  
2 load caused by being connected to the faulted lines, and (3) damage to or destruction of  
3 various UPS components, including fuses (not shown) contained in output inverter 511.  
4 When the utility disconnect switch 502 is naturally commutated, *e.g.*, is constructed with  
5 SCRs, the voltage collapse at input 501 associated with many types of faults in  
6 combination with the voltage generated by output inverter 511 naturally causes the  
7 switching devices 502a and 502b to commutate. This is so because the voltage on the  
8 UPS bus will be higher in magnitude than that on the faulted input line, thereby driving  
9 the current through the SCR to zero.

10 However, for certain types of faults, as described above, the voltage at input 501  
11 may increase in magnitude, thus preventing the natural commutation of the SCRs 502,  
12 because the utility voltage is forcing the line current to increase in magnitude, rather than  
13 approaching zero. If the magnitude of this fault is within the correction range of the  
14 series inverter 507, it is possible for the series inverter to block the disturbance from  
15 reaching the system output bus. The correction range of the series inverter is limited by  
16 design, primarily due to economic and efficiency concerns. Therefore, in most  
17 applications, input faults that cause transients outside the correction range of the series  
18 inverter can be expected. To minimize the impact of this transient, the present invention  
19 uses one or both of the inverters 507 and 511 to force commutate the utility disconnect  
20 switch. Without the ability to quickly open the input switch, the series inverter is  
21 susceptible to output faults; that is, an output short will cause the input line voltage to be  
22 imposed across the series inverter. This voltage may be greater than the rating of the

1 series inverter and may cause damage to it. A method of commutating static switch  
2 thyristors using an inverter in a UPS is disclosed in U.S. Patent 4,782,241.

3 One method of commutating the utility disconnect is to use only the main inverter  
4 411. When a fault is detected that causes the voltage at the input 501 to change such that  
5 the line current will increase in magnitude, the main inverter controller commands the  
6 main inverter switches to a state that applies a voltage that causes the inverter current to  
7 approach the load current. When the inverter current equals the load current, line current  
8 will have been forced to zero, and commutation will have been achieved. In practice, it is  
9 only necessary for the controller to have knowledge of the direction of the line current  
10 and to select the inverter switch that provides the same voltage polarity as the line current  
11 polarity. Although the resulting voltage transient seen at output 515 is somewhat  
12 extreme, the short duration required is such that the load is not disrupted. Nor should the  
13 inverter experience overcurrent stress. Typical SCRs used for static switch applications  
14 will commute and be capable of blocking applied voltage in a few hundreds of  
15 microseconds.

16 The critical load disruption may also be minimized using only the series inverter  
17 507. However, the limited ratings of series inverter 507 require that the fault be detected  
18 early before the voltage at input 501 is out of the range in which the series inverter has  
19 sufficient capacity to force commute the input SCRs. Another alternative for  
20 minimizing disruption to the critical load is to use the series inverter at its maximum  
21 capacity and make up the additional energy required to null the current flow through the  
22 SCRs using the main inverter. Because the series inverter is also used to null the current



1 flow, the requirements on the main inverter are reduced, thereby reducing the output  
2 voltage distortion seen by the critical load and likely providing faster commutation.

3 The fast utility disconnect may also be constructed using gate commutated  
4 switching devices, such as power transistors. This alternative embodiment is illustrated  
5 in Fig. 6. A gate commutated switching device differs from a naturally commutated  
6 switching device in that the device may be turned off simply by removing the gate pulse.  
7 Those skilled in the art recognize that a gate commutated switch may also be made using  
8 SCRs employing forced commutation.

9 Because a gate commutated switch may be opened when current is flowing  
10 through the device, it is usually necessary to add some type of clamping circuit to the  
11 switch to prevent its destruction from interrupting the current. However, if the equivalent  
12 inductance seen by the switching devices is sufficiently low, the switching devices can  
13 safely interrupt the current without damage, and a clamping circuit is not required.

14 One possible clamping circuit is shown in Fig. 6, and comprises four diodes 601,  
15 602, 603, and 604. Diodes 601 and 602 are connected between the input of the fast utility  
16 disconnect and the DC bus. Diodes 603 and 604 are connected between the output of the  
17 fast utility disconnect switch and the DC bus. The diodes are arranged such that a  
18 voltage excursion greater than either the positive or negative DC bus voltage on either  
19 side of the fast utility disconnect will be clamped to the DC bus voltage. The excess  
20 energy from such a voltage excursion will be absorbed by the battery 508 and DC bus  
21 capacitors 510a and 510b.

22 An alternative clamping circuit is shown in Fig. 7. The clamping circuit  
23 comprises four diodes 701, 702, 703, and 704 and a capacitor 705. The principle of



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1 utility disconnect 1001 and comprises diodes 1002 and 1003 and capacitors 1004 and  
2 1005. Diode 1002 has its anode coupled to the input side of fast utility disconnect 1001  
3 and its cathode coupled to a first terminal of capacitor 1004. Similarly diode 1003 has its  
4 cathode coupled to the input side of fast utility disconnect 1001 and its anode coupled to  
5 a second terminal of capacitor 1005. The second terminal of capacitor 1004 and the first  
6 terminal of capacitor 1005 are coupled together and are coupled to ground. In the event  
7 of a transient voltage excursion associated with the inductive reactance of the power line  
8 circuit and caused by commutation of the fast utility disconnect, diode 1002 (for positive  
9 voltage excursions) or diode 1003 (for negative voltage excursions) will conduct  
10 allowing capacitor 1004 or 1005 respectively to absorb the energy associated with the  
11 transient voltage excursion.

12 Finally, another clamping circuit for use with a self commutated fast utility  
13 disconnect is illustrated in Fig. 11. The clamping circuit comprises two voltage limiting  
14 diodes 1101 and 1102 connected to the input side of fast utility disconnect 1103. The  
15 cathode of voltage limiting diode 1101 is coupled to the input of fast utility disconnect  
16 1103, with the anode being coupled to the anode of voltage limiting diode 1102. The  
17 cathode of voltage limiting diode 1102 is coupled to ground, allowing either positive or  
18 negative transient voltage excursions to be sunk to ground.

19 The voltage limiting diodes 1101 and 1002 could be replaced with any other bi-  
20 directional transient voltage suppression device, for example, varistors, including metal  
21 oxide varistors, back-to-back transorbs, breakdown diodes (Shockley diodes, diacs),  
22 carbon piles, gas discharge devices, etc.

1 To force or assist commutation of the static switch, it is necessary to know the  
2 direction of the current flowing through the static switch. One way of determining the  
3 current direction is to use a current sensor that produces an analog signal. Connection of  
4 such a sensor 801 is illustrated in Fig. 8. Alternatively, the direction of the current can be  
5 determined by observing the voltage across the static switch. Connection of the required  
6 voltage sensor 802 is also illustrated in Fig. 8. The voltage sensor technique is preferred,  
7 as it is less sensitive to offset errors.

8 Additional modifications and adaptations of the present invention will be obvious  
9 to one of ordinary skill in the art, and it is understood that the invention is not to be  
10 limited to the particular illustrative embodiments set forth herein. It is intended that the  
11 invention embrace all such modified forms as come within the scope of the following  
12 claims.

## REFERENCES

The following references, to the extent that they provide exemplary procedural or other details supplementary to those set forth herein, are specifically incorporated herein by reference.

U.S. Patent No. 4,782,241, entitled “Uninterruptible Power Supply Apparatus and Power Path Transfer Method.”

## SEQUENCE LISTING

1

2

Not Applicable